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RESEARCH ARTICLE

# Load behaviors of a prefabricated wood framing house during lifting and transportation

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**Abstract** Lifting for handling and flatbed truck transportation to the job site are important processes during manufacture of prefabricated wooden construction units like mini homes and building modules. Significant damage can occur to sections or components of units during these operations. Although damage usually will not impair its structural safety, it is costly to fix and causes the public to perceive prefabricated wooden buildings as low quality products. Field observations and preliminary numerical models for prefabricated units subject to lifting and transportation forces are summarized here. Once fully developed and verified, models will support the creation of damage mitigation strategies centered on structural details indicating how units are to be supported during lifting and transportation.

**Key words** prefabricated house, wooden timber construction, load behavior, mini home

## 1 Introduction

Proper design of consumer goods involves assessing the likely effects of forces that could occur during manufacture and service phases of their lifetime. These include buildings made of wood, especially prefabricated construction units like mini homes and building modules. Lifting for handling and flatbed truck transportation to the job site are manufacturing processes which can generate potentially damaging forces in the units. Field observations show that significant damage can occur to sections or components of units as a result of improper lifting, improper support of units on flatbed trucks, road vibrations and wind pressures during transportation. It should be noted that because of regulations governing the size of units that can be transported on public roads, units are always restricted in height to one storey plus a floor platform and a roof in the case of mini homes. Typically damage does not impair structural safety and can be repaired on site. However, damage is costly to remedy and creates a negative public perception of the quality attainable with prefabricated systems. The most visible damages are cracks showing up in nominally non-structural plasterboard linings. Usually cracks in plasterboard occur in walls near corners of door and window openings and in ceilings adjacent to wall to roof junctions. The current approach to minimizing damage is to add significant amounts of 'extra' framing material, relative to what is required by building codes and applicable when the units are installed and in service (Path, 2003). However, largely to the surprise of manufacturers, this practice can actually accentuate problems (Asiz et al., 2005). From a structural point of view, the problem occurs when inappropriately placed reinforcing material concentrates stresses at vulnerable locations. Therefore, information on the magnitudes of forces generated during handling and transportation of units is crucial in order to reduce damage. In our paper we discuss a field test program and the development of three-dimensional finite element (FE) models based on a typical North American prefabricated wooden mini home.

## 2 Materials and method

### 2.1 Field test

The mini home tested represents the longest and widest prefabricated unit allowed to be transported on public roads in North America (Fig. 1). Such units are of the type prone to damage during handling and transportation processes.

During field tests, which insisted of loading on and off the factory floor and transportation under three road conditions (rural roads, provincial roads and express highways), the following parameters were measured: deformation, vibration and wind speed, direction and pressure. Locations $C_0$, $C_1$, $C_2$ and $C_3$ in Fig. 1a are positions of accelerometers sensing the effects of impacts and road vibrations. Eleven deformation sensors were installed in the living room area which had no internal partitions and several large openings (doors and windows), because that is where damage is frequently observed. Eighteen pressure taps were installed on exterior wall surfaces with six placed on each of the long side elevations, four on the

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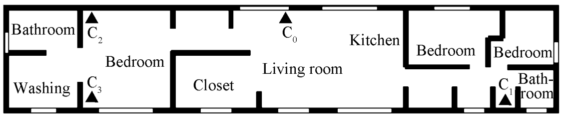



a. Plan view

b. Typical elevation

**Fig. 1** Tested mini home with dimensions of 4.88 m× 22.6 m

front elevation (face near the truck cab) and two on the rear elevation. The pressure taps measured differential wind pressures applied to walls (external minus internal pressure). No pressure taps were installed on the roof surface because that would have caused damage unacceptable to the owner. An anemometer measured wind speed and direction at the end of the unit just below the level of the eaves. All sensors were connected to high-speed data recording equipment. The deformation sensor and pressure tap locations are shown in Fig. 2.

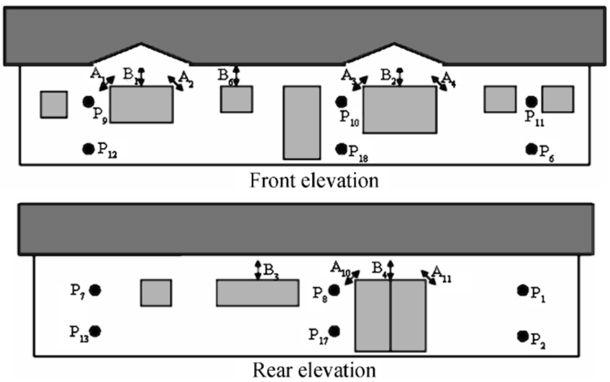



**Fig. 2** Deformation sensor and pressure tap locations. P designates pressure sensor on penetrating wall; A and B designate deformation sensors on interior plasterboard linings.

### 2.2 Numerical models

Numerical models of the prefab mini home during lifting and transportation were developed using the SAP2000 finite element software (Anonymous, 2005). Orthotropic shell elements were used to represent wall and roof sheathing, drywall (plasterboard) and floor sheathing. Lumber framing in walls, floor and roof were modeled using frame elements. The interfaces/connections between framing members, and between framing and other components were modeled using link elements composed of springs allowing axial, shear and rotational movements. Mechanical properties of elements were derived from test data and literature databases (Mi et al., 2004). For model simulations of transportation by flatbed trucks, boundary interfaces between the building unit and truck-bed were simulated using link elements. Major loads imposed on building modules during lifting are gravity forces. During transportation wind pressures obtained from field test were the major loads. So far the effect of vibration due to road roughness and non-steady state motions has not been assessed by modeling. This is reasonable because magnitudes of resulting forces were not critical during our field tests.

## 3 Results and discussion

From our deliberate observations of the whole procedure we can draw the inference that the majority of cracks occurred in the first fifty meters and the last fifty meters inside the back yard of the Prestige home. Severe cracks occurred when the house was loaded on and offloaded from the trailer in the back yard. These can be classified into three categories: long and horizontal cracks on the two side walls (two are located on the back side wall in the third bedroom and living room, respectively; one is located on the front side wall in the kitchen); long and vertical cracks on the ceiling in the kitchen; 45º cracks on the corners of the windows and doors in the kitchen and living room. Apart from the timing when cracks occurred, another interesting phenomenon was that severe cracks were largely concentrated in the middle part of the mini home, i.e., in the living room and kitchen. At the same time almost no cracks occurred in the two end parts (the three bed rooms, a bath room and the wash room). It was thought that two specific operations could cause this problem during the whole procedure. The first one was to lay the house on the six steel saddles before loading and after unloading. The surface of the back yard was uneven and bumpy gravel. The six saddles, which were supposed to support the house, were far from the even horizontal level required, so that the different sections of the house were severely twisted and cracked. The distortion was so severe that the door could not be opened in our case study. The workers had to repeat the loading and unloading procedure so that they could use wood shims to adjust the height of the saddles to open the door. This operation caused the most 45º cracks and vertical cracks on the ceiling. The second operation was that four jacks were used in two pairs during lowering of the trailer with the mini home to the normal wheel support level. The front pair was lowered first until wheel height was

reached and then the two rear jacks were lowered. The long and horizontal cracks on the side walls occurred at this stage. The top and bottom parts separated from the horizontal transverse plane; this worked like a shear entity because of the interaction of inertial force, friction force and gravity. We did not observe any contribution to the cracks from transportation. There are two possibilities that should be analyzed and proven. The first is that there is no damage as a result of transportation. The second possibility is that the cracks, which could have occurred during transportation, had already been incurred during loading procedures before transportation or during offloading afterwards.

Table 1 presents absolute deformations recorded during lifting and transportation processes. From the deformation data, the largest displacements during lifting occurred at the corners of window openings, followed by displacements at the internal junctions between walls and ceilings. During transportation some significant displacements were detected but those deformations were mainly caused by already existing damages initiated during lifting in the factory yard.

The deformations predicted at various sensor locations are shown in Table 2 and typical predicted deformed shapes are shown in Fig. 3. Deformations from static load FE models were not entirely consistent with those measured during the field tests. This is attributed to inaccurate modeling of plasterboard to framing connections/interfaces. Ongoing work will include upgrading models in this respect and to incorporate failure criteria for initiation of damage directly to plasterboard linings. All the same, the models correctly indicate the vulnerable regions and components in prefabricated mini homes. We presume the same is true for prefabricated building modules. Although for the tested mini home acceleration/impact induced forces were not critical, FE models for these variables will be developed because such findings may not always hold true. The issue of coupled fluid (air) and structure interaction will also be investigated. When fully developed, the models will aid in the creation of strategies to mitigate damage centered on structural details and indicate how units are to be supported during lifting and transportation processes.

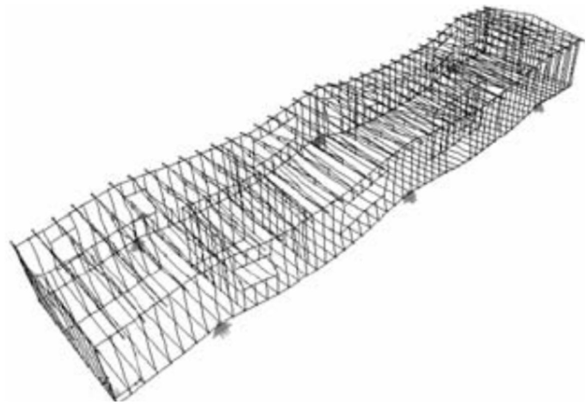
**Table 1** Comparison of absolute deformations (unit: mm)

| Process | A1 | A2 | A3 | A4 | A10 | A11 | B1 | B2 | B3 | B4 | B6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lifting | 0.12 | 0.13 | 0.20 | 0.10 | 0.84 | 1.43 | 0.01 | 0.04 | 0.13 | 0.12 | 0.01 |
| Transport | 1.04 | 0.65 | 1.01 | 0.04 | 1.14 | 0.41 | 0.01 | 0.05 | 0.17 | 0.25 | 0.03 |

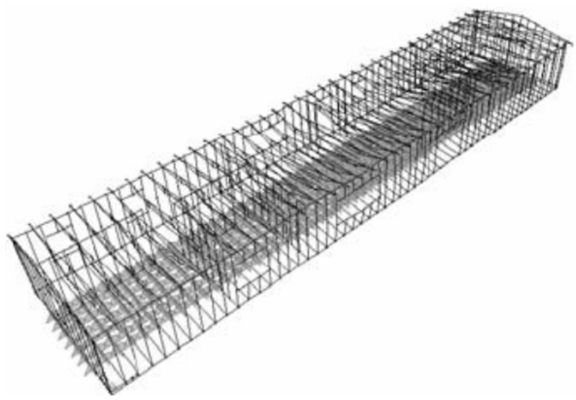
Note: Notation for the deformation sensors and their location are shown in Fig. 2.

**Table 2** Absolute deformations obtained from FE modeling (unit: mm)

| Process | A1 | A2 | A3 | A4 | A10 | A11 | B1 | B2 | B3 | B4 | B6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lifting | 0.05 | 1.41 | 0.44 | 1.48 | 0.67 | 1.55 | 0.73 | 0.99 | 1.21 | 1.15 | 1.67 |
| Transport | 0.41 | 0.37 | 0.38 | 0.38 | 0.40 | 0.37 | 0.43 | 0.46 | 0.52 | 0.41 | 0.39 |



a. During lifting



b. During transportation

**Fig. 3** Deformed FE model of mini home

## 4 Conclusions

The majority of cracks and damages occurred during the operation in the back yard of the Prestige factory. The cracks developed severely because of road vibration, impact and wind pressure during transportation. The field test data and FE modeling analysis proved that the largest displacements were at the corners of window openings, followed by displacements at the internal junctions between walls and ceilings. Deformations from static load FE models were not entirely consistent with those measured during field tests. It is thought that this inconsistency could be attributed to inaccurate modeling of plasterboard to framing connections/interfaces.

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